Application of PHSD to KEK-PS E325 experiment

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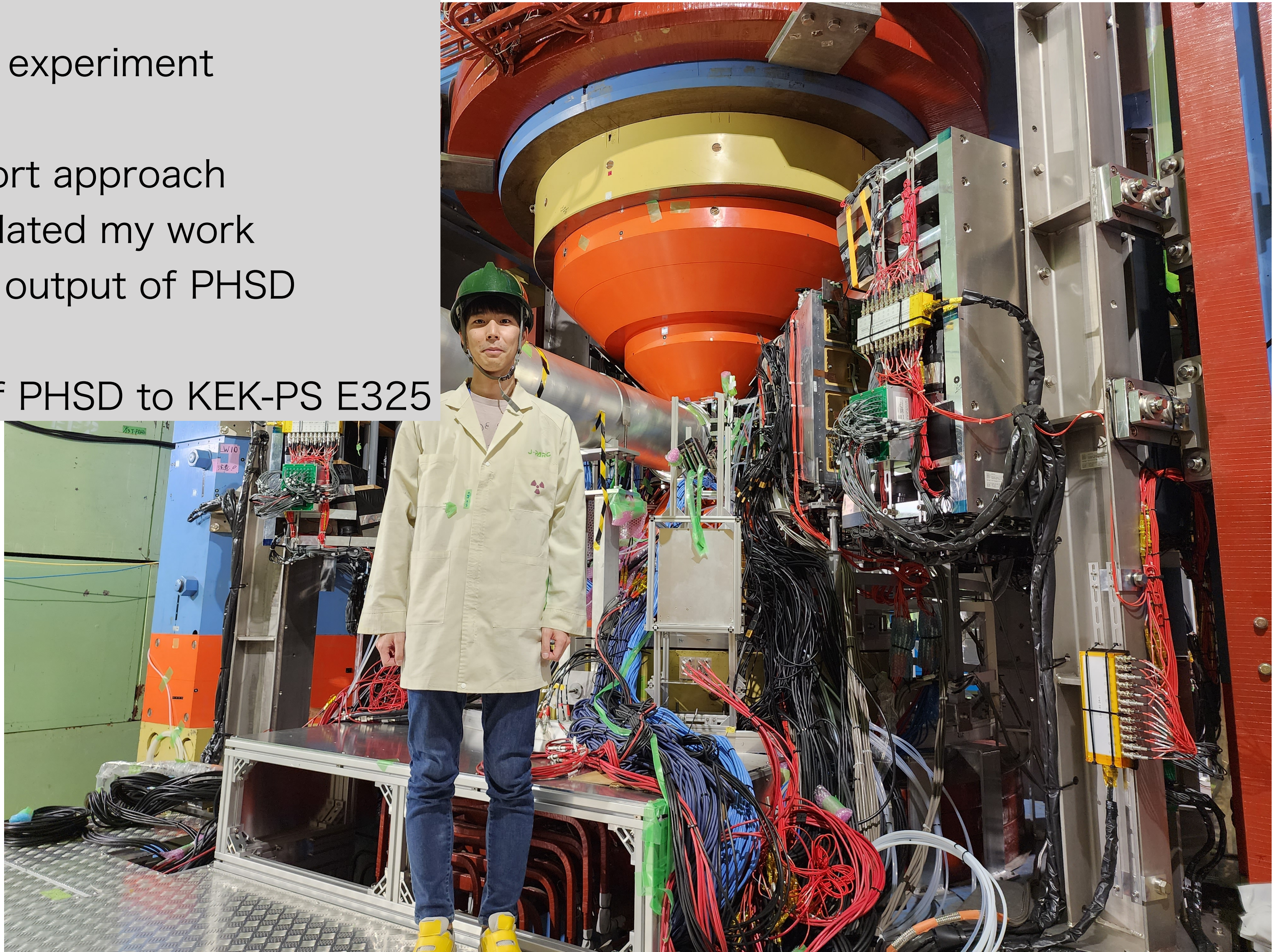
Outline

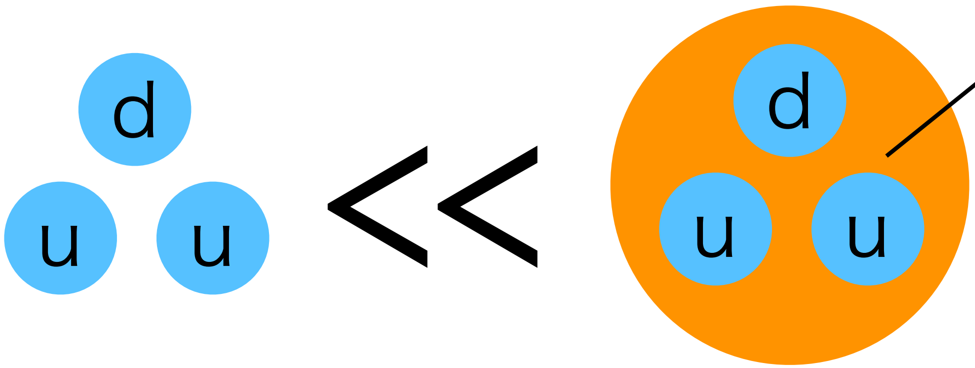
- Physics motivation
- KEK-PS E325 experiment
- PHSD transport approach
  - Features related my work
  - Elementary output of PHSD
- Application of PHSD to KEK-PS E325



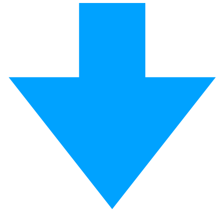
physics motivation

Origin of hadron mass

Current quark ~ MeV/c²　　Hadron ~GeV/c²

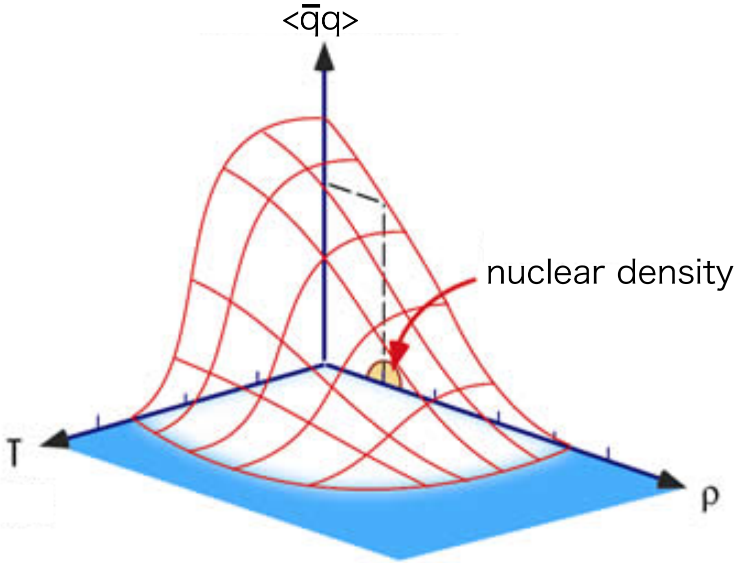


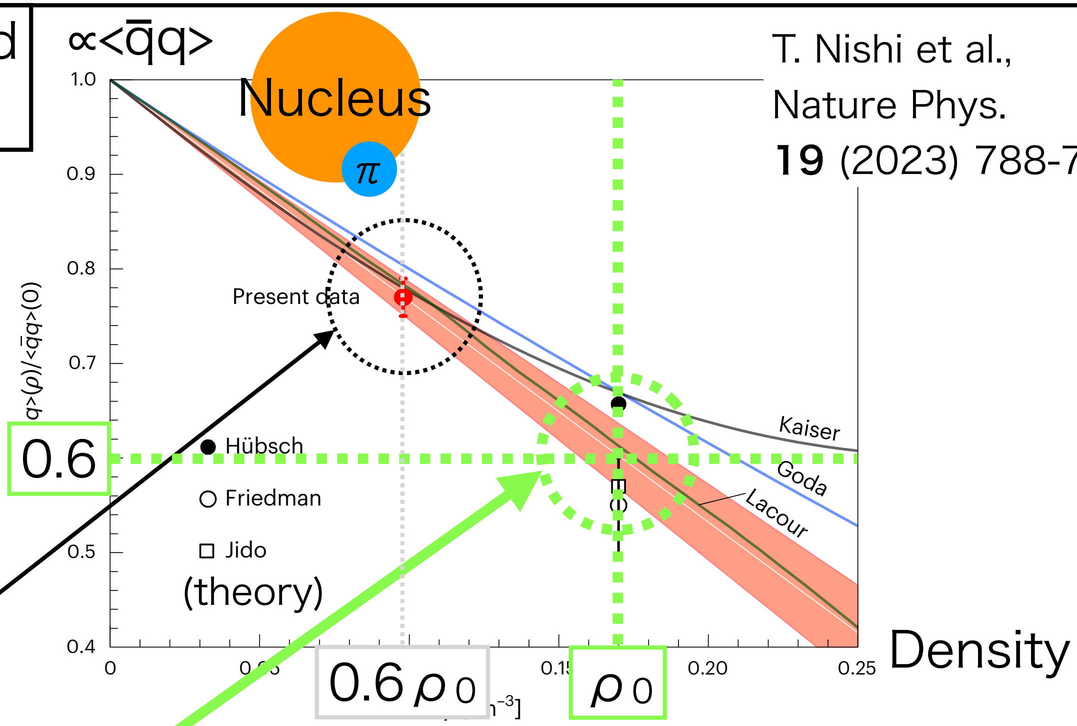
Contribution of Higgs is a few %



Spontaneous breaking of chiral symmetry

Chiral symmetry breaking is suggested to be restored at finite density





T. Nishi et al., Nature Phys. **19** (2023) 788-793

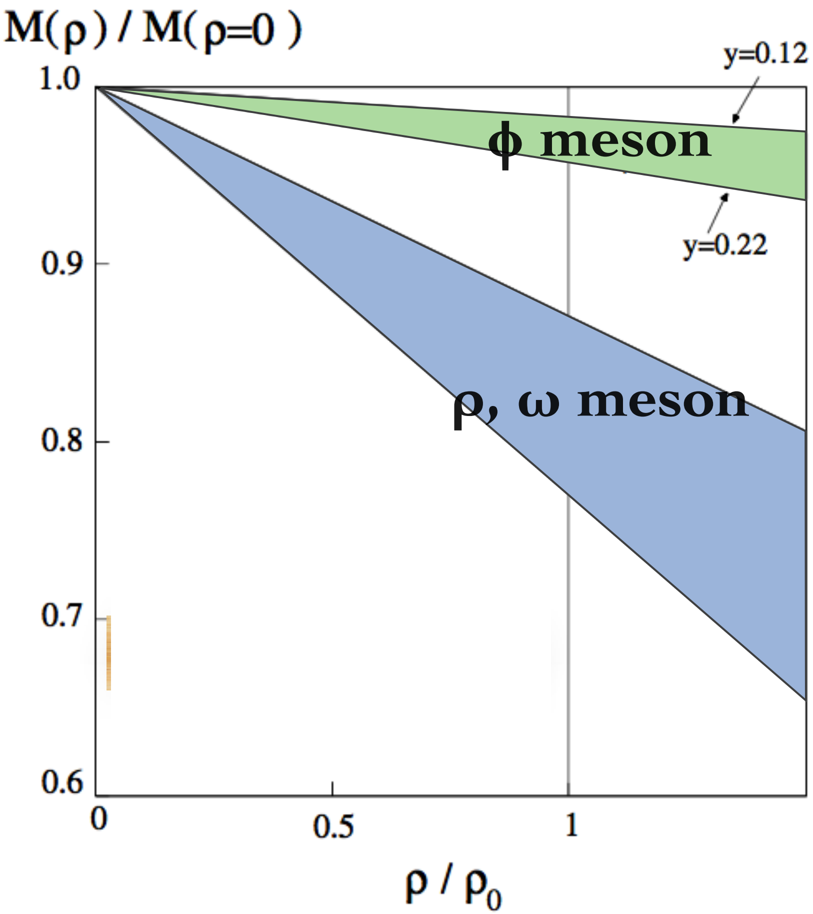
Determined by **optical potential** of π-atom

Measurement of **hadron spectrum** at nuclear density is needed.

Vector meson in nuclei

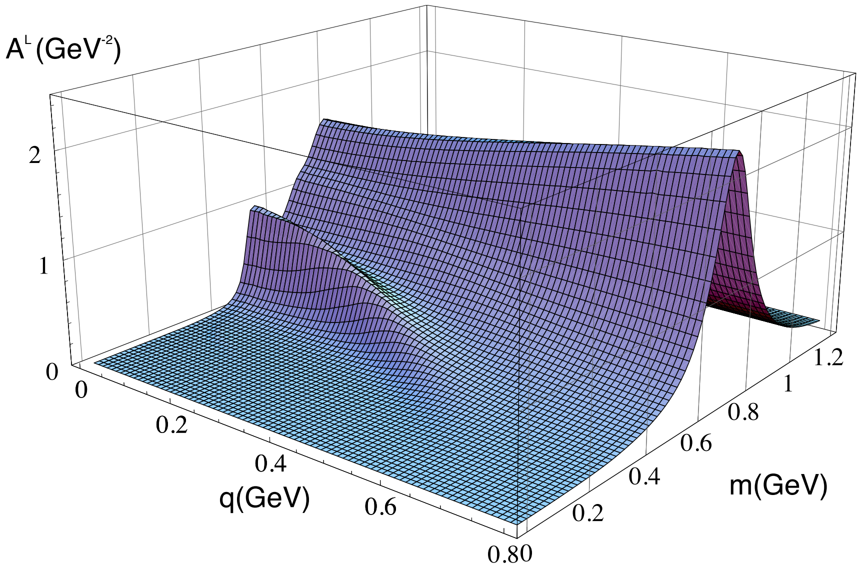
Vector mesons decay into lepton pair.

-> Avoid strong final state interaction with nucleus



T. Hatsuda and S. H. Lee,
Phys. Rev. C **46**, R34 (1992)

Calculation from QCD sum rule



M. Post and U. Mosel, Nucl. Phys. A **699** (2002) 169c-172c

ρ meson in nuclear medium

- Taking baryon resonances into account
- Note that spectral modification may be not just simple mass shift and width broadening.
  -> This effect is measurable
  (Analysis needs to be updated)

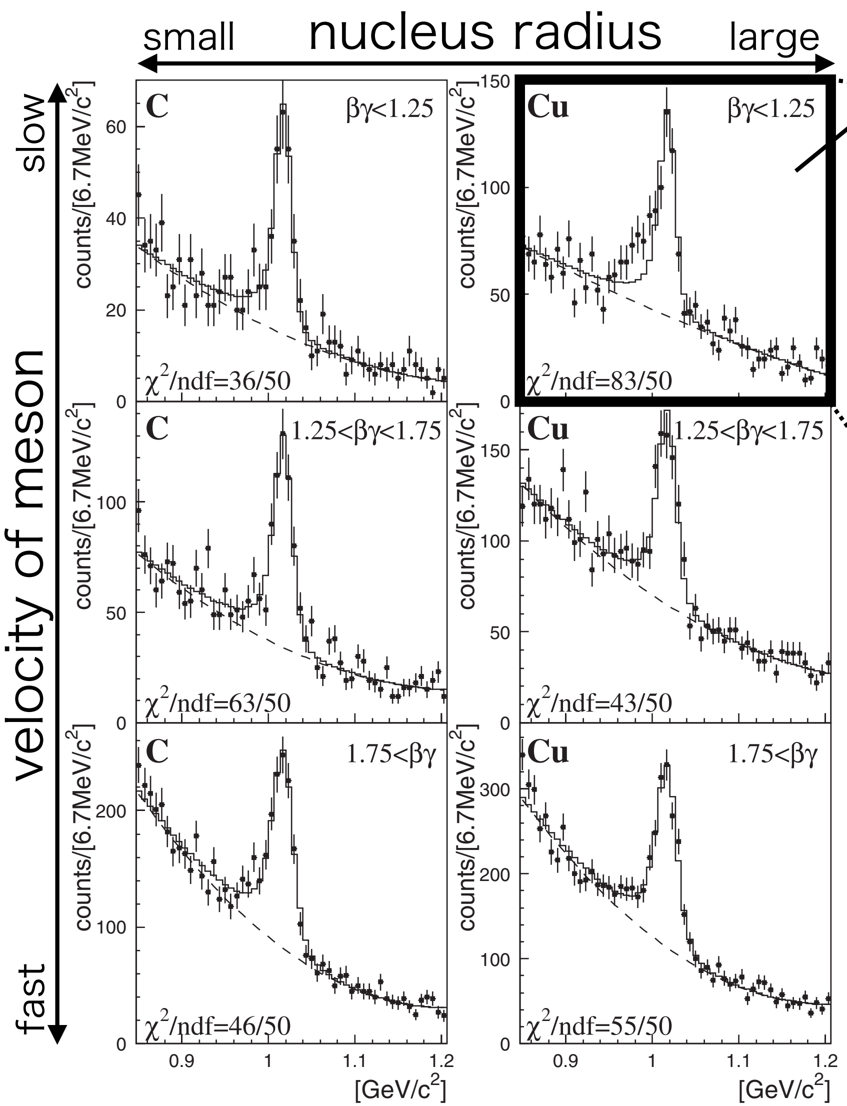
KEK-PS E325 experiment

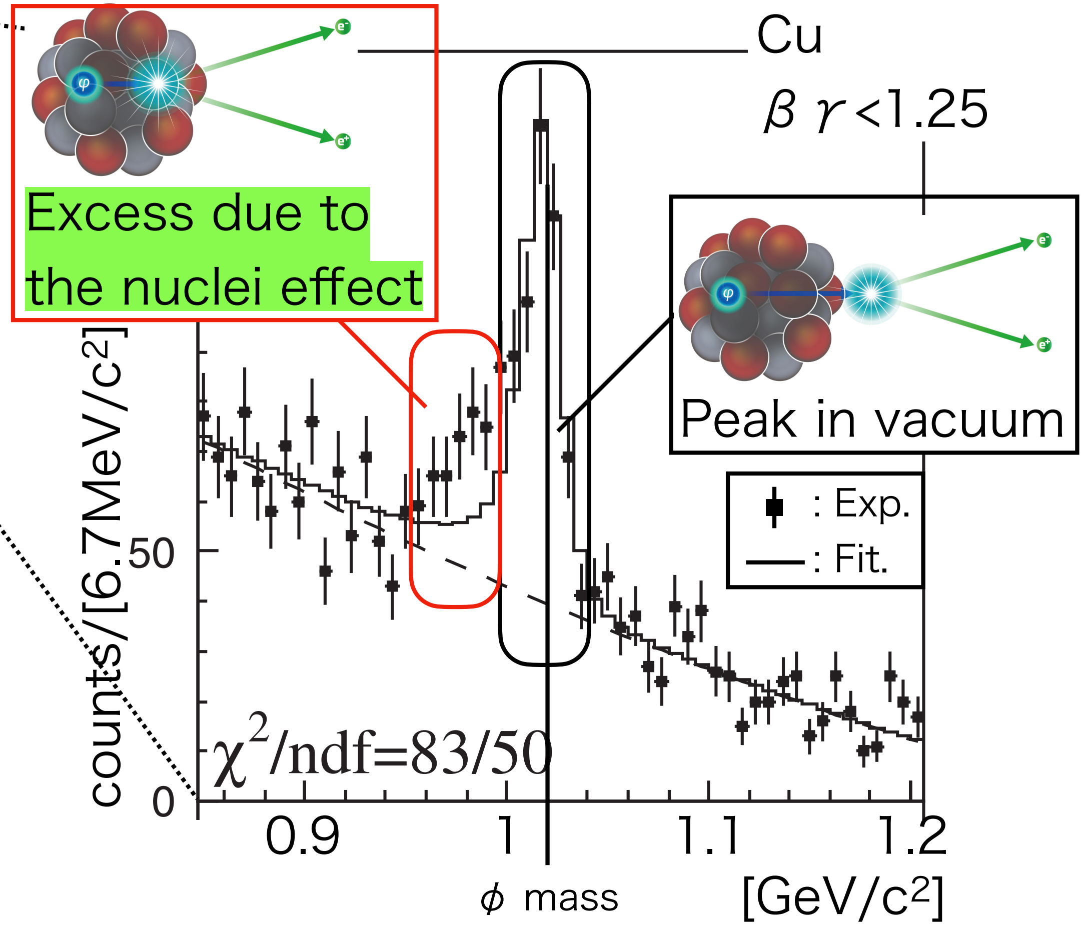
KEK-PS E325 experiment

12 GeV p + (C, Cu) -> (ρ, ω, ϕ) + X
(ρ, ω, ϕ) -> e^+e^-
Data were taken in 2001-2002

- Flight length of ϕ : ~50 fm ($\beta\gamma$ ~1)
- Radius of nucleus : <10 fm

Highest probability of decay in nuclei

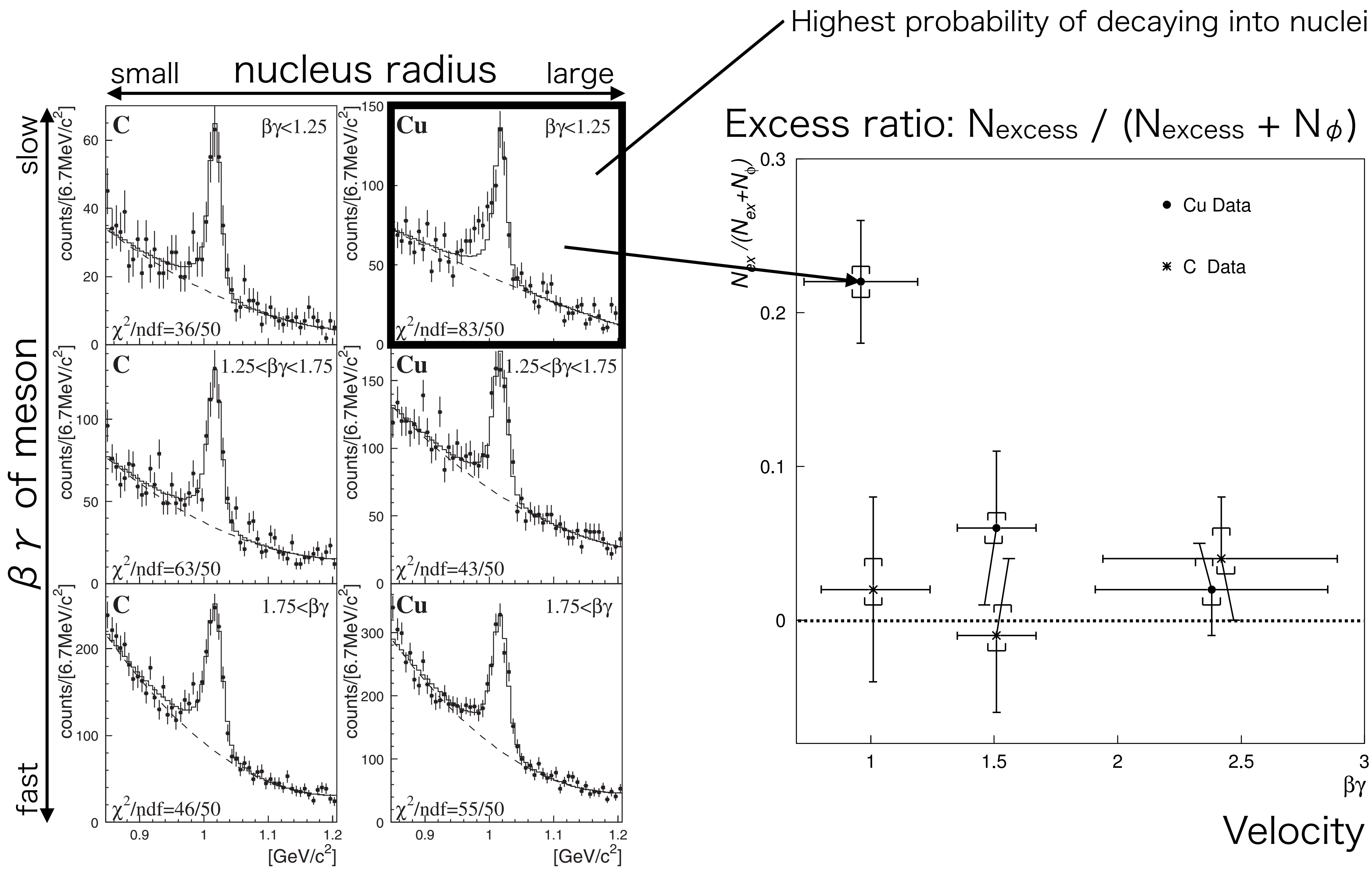




R. Muto, et. al., Phys. Rev. Lett., 98, 042501(2007)

KEK-PS E325 experiment

Significant Spectral modification was observed
in samples with the highest probability of decay in nuclei.



Previous analysis

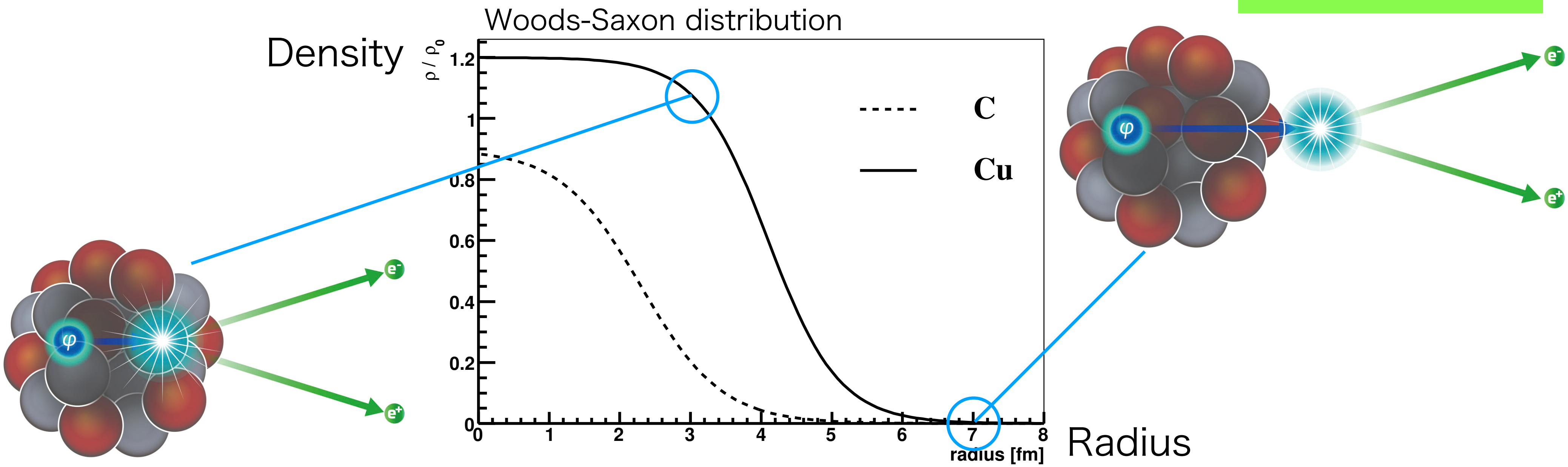
Parameterize spectral modification with mass shift and width broadening

$$m(\rho) = (1 - k_1 \frac{\rho}{\rho_0}) m_0$$

$$\Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0}) \Gamma_0$$

The flight length of ϕ is longer than the radius of nuclei.

-> ϕ decays at various densities, from nuclear density to vacuum (not only 0 or ρ_0).



・Simulate densities at ϕ meson decays

・Fit experimental data with simulated spectrum

for various k_1 and k_2.

Previous analysis

Production point of ϕ

- Follows Woods-Saxon distribution

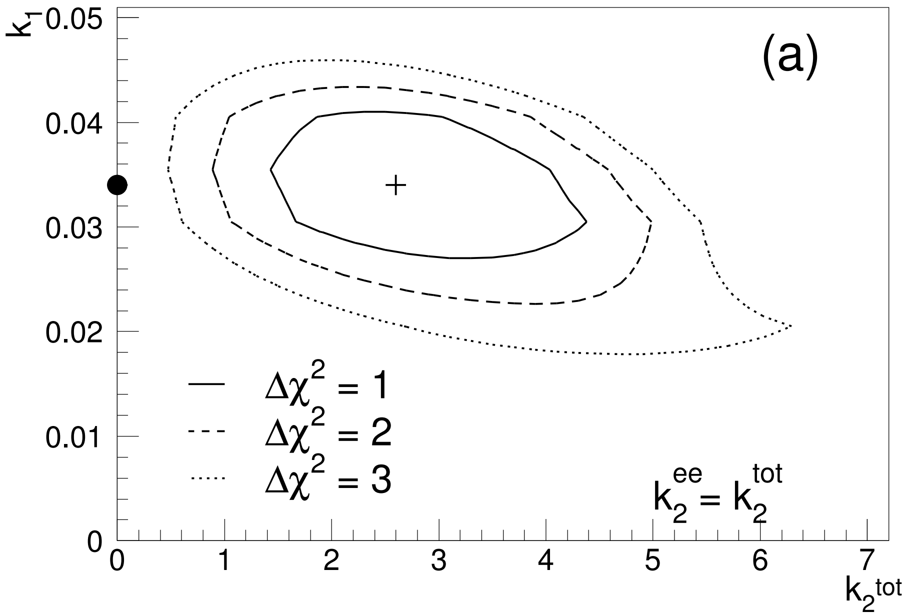
Momentum of ϕ

- Measured experimentally
- Well reproduced by JAM

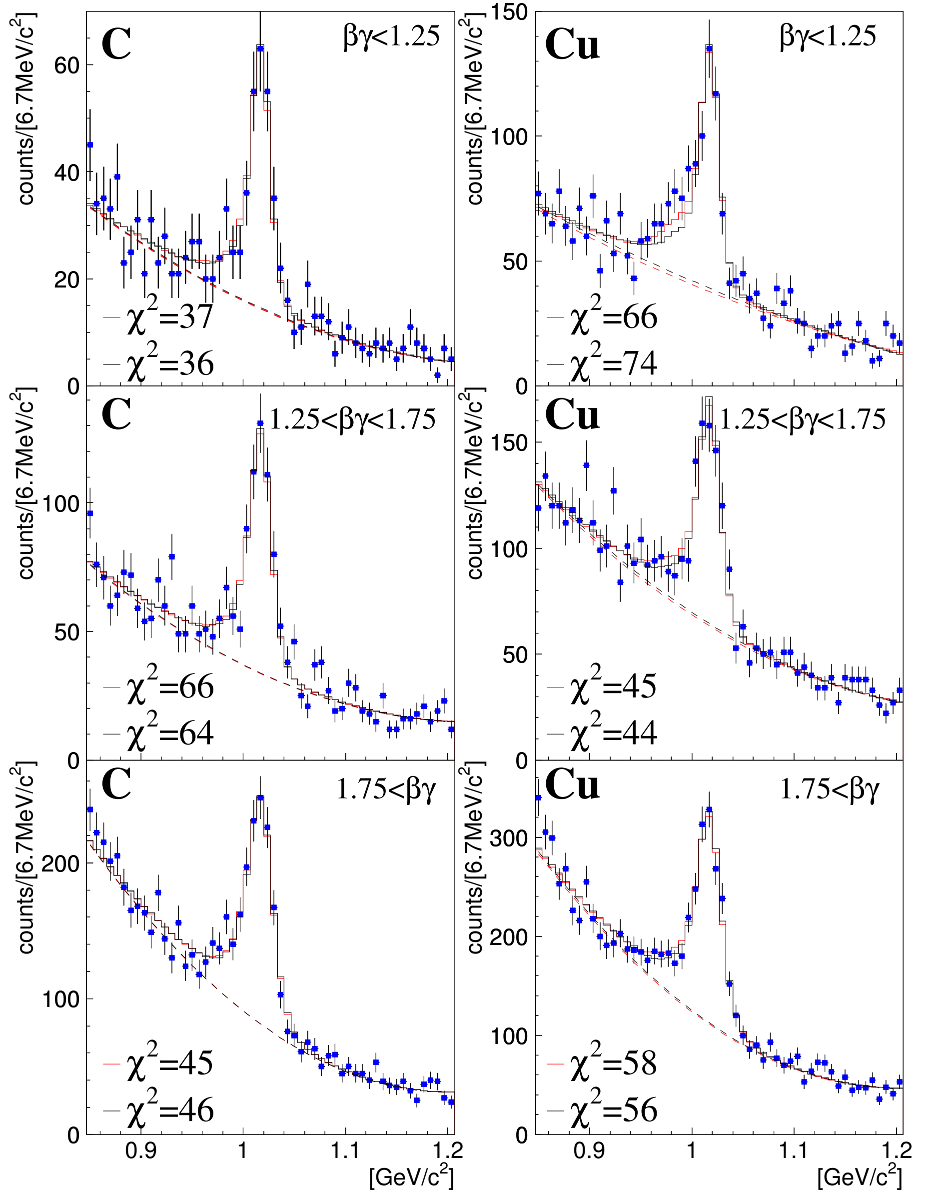
  JAM: hadronic cascade model

Density distribution after pA reaction

- Follows Woods-Saxon distribution



Sum of χ^2 of the 6 spectrums (regarding minimum value as 0)



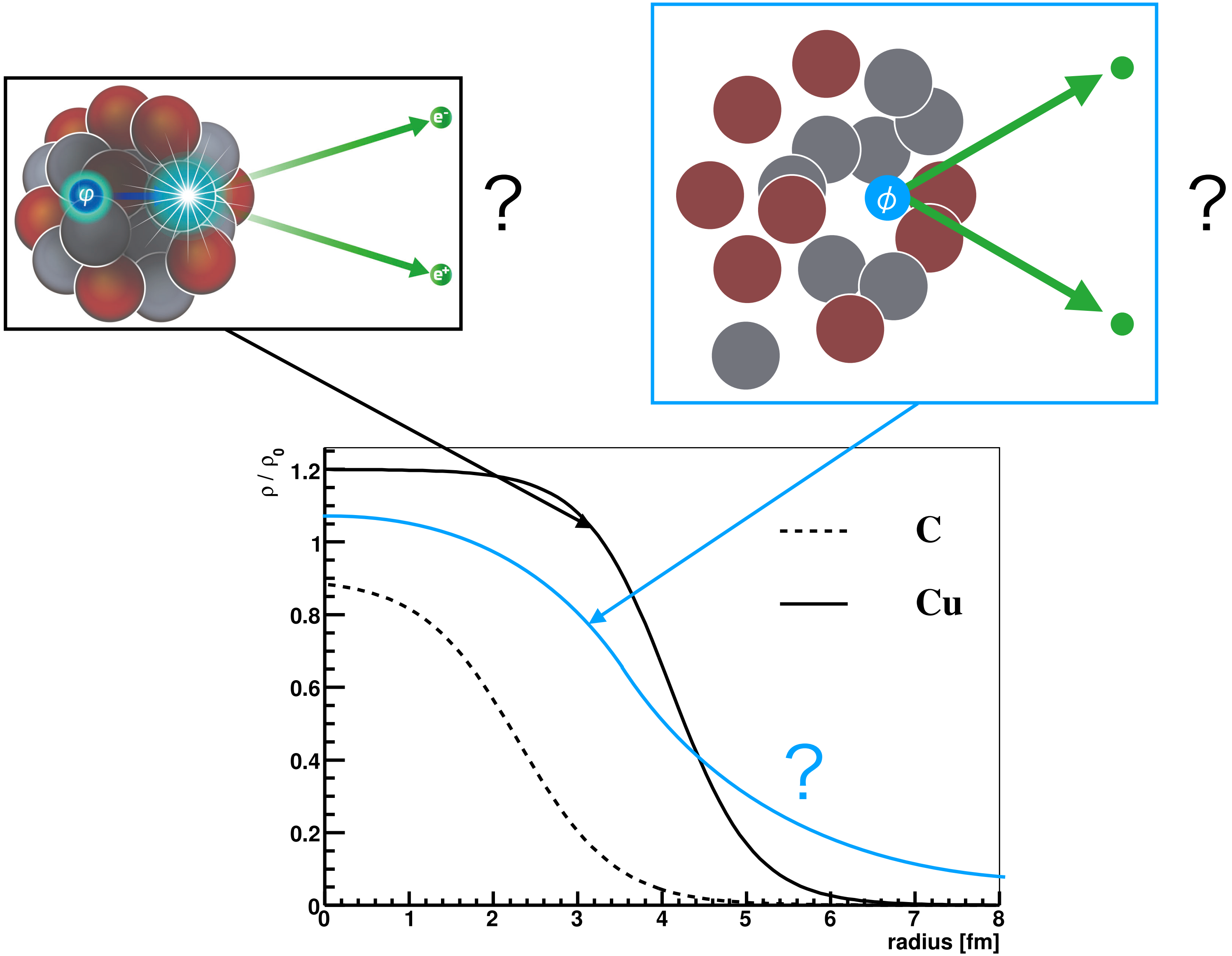
$m(\rho) = (1 - 0.034 \times \rho/\rho_0) \times m_0$

$\Gamma(\rho) = (1 + 2.6 \times \rho/\rho_0) \times \Gamma_0$

In what density does ϕ decay?

Space time evolution of nucleon distribution after the pA reaction may exist.

-> The density that ϕ feel at decay is non-trivial.



PHSD transport approach

New approach using PHSD

Parton-Hadron-String Dynamics (PHSD) transport approach

- A microscopic covariant dynamical approach
  for strongly interacting systems in and out-of equilibrium

- Simulate the time evolution of ϕ, nucleons and other hadrons
  during the pA reaction.

- Treat nuclei as nucleons interacting with ϕ and other hadrons
  <-> previous analysis: just an external field

- Consider spectral modification in time evolution.

-> More accurate information on

- the production point of ϕ
- the density distribution after pA reaction

can be obtained.

Analysis method

- Make spectra that can be compared with experimental data.
  - Make data of ϕ by PHSD (various mass shift and broadening parameters)
  - Add internal radiative correction (IRC) by PHOTOS
  - Decay Isotropically
  - Simulate tracks of e^+e^- by Geant4
  - Add detector resolution and efficiency
  - Fit tracks from detector responses
  - Reconstruct spectrum

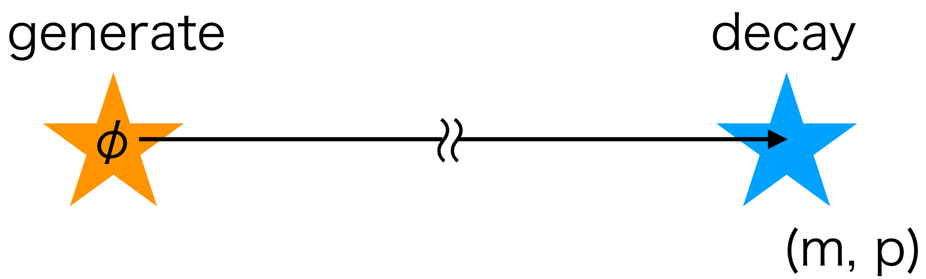
Detail:

-> Nakai-san's talk

Time integration method

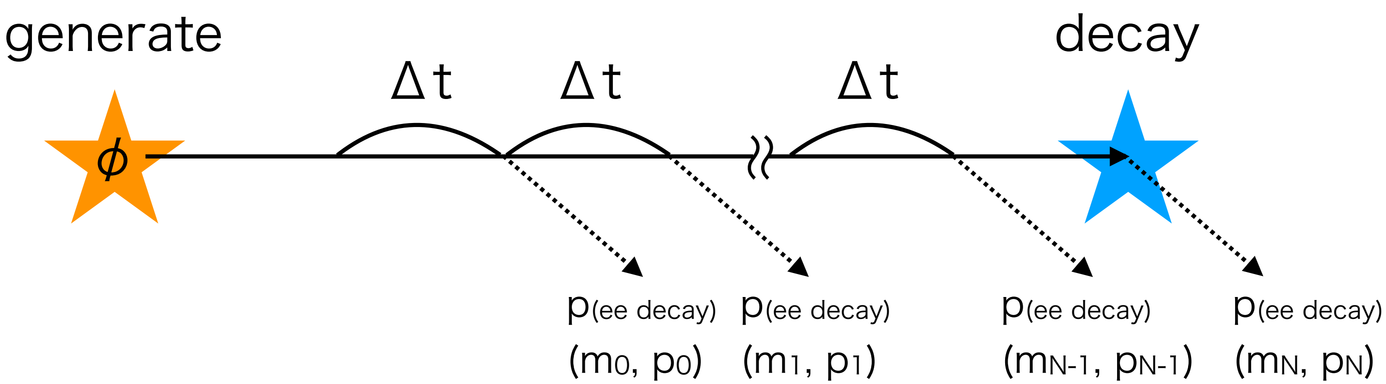
In PHSD, to increase statistics efficiently, time integration method is used.

Simple method



1 event/phi

Time integration method



N events/phi

(※Correlation exists)

- Decay into e^+e^- "virtually" at each time step
- Treated with weights for the probability of e^+e^- decay

e^+e^- decay probability in PHSD $= 1 - \exp\left(-\frac{\Gamma_{ee}\Delta t}{\hbar\gamma}\right) \sim \frac{\Gamma_{ee}\Delta t}{\hbar\gamma} \quad \left(\Gamma_{ee} \propto \frac{m_{pole}^4}{m^3}\right)$

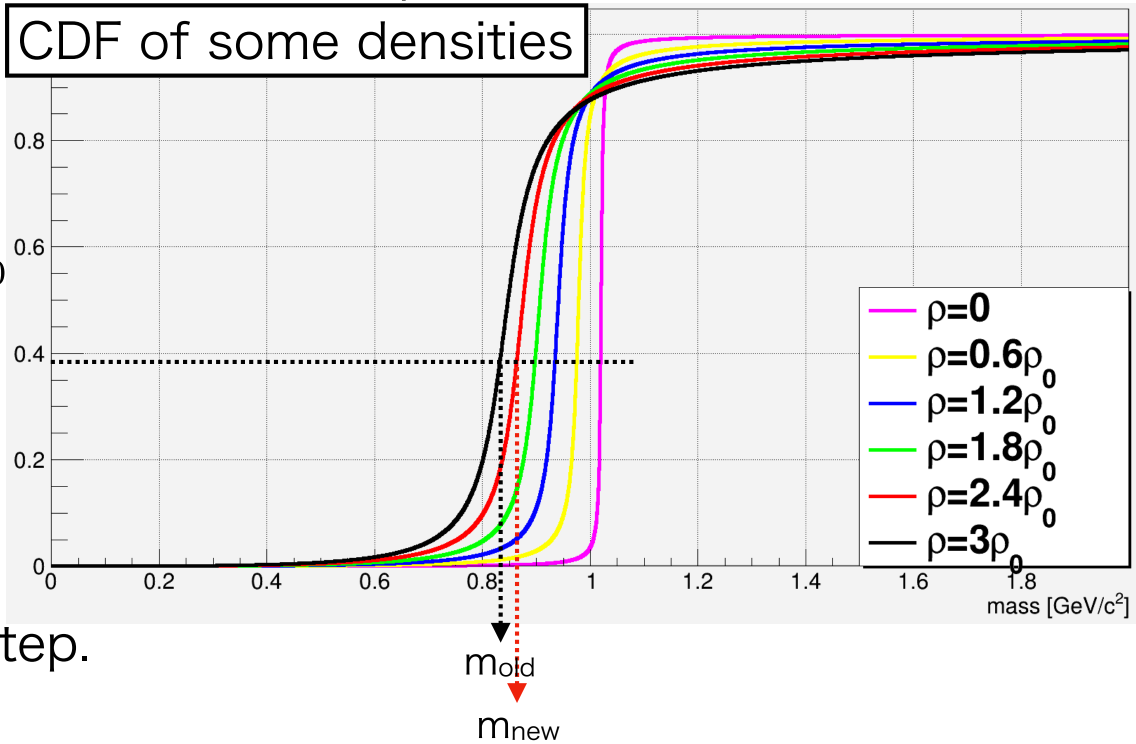
Time evolution with spectral modification

- For each of the 51 density (0, 0.06 ρ_0, ⋯, 3 ρ_0), cumulative distribution functions (CDF) of relativistic Breit-Wigner are calculated and the values are stored for each mass of 0.4 MeV/c^2.

BW: $A(m,\rho) = \frac{2}{\pi} m^2 \Gamma \frac{1}{(m^2 - m_{pole}^2)^2 + \Gamma^2 m^2}$

$m_{pole}(\rho) = \frac{m_0}{1 + \frac{k_1}{1-k_1}\frac{\rho}{\rho_0}}$, $\Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0})\Gamma_0$

(k_1: shift parameter,
k_2: broadening parameter)



- ϕ moves and interacts every time step.

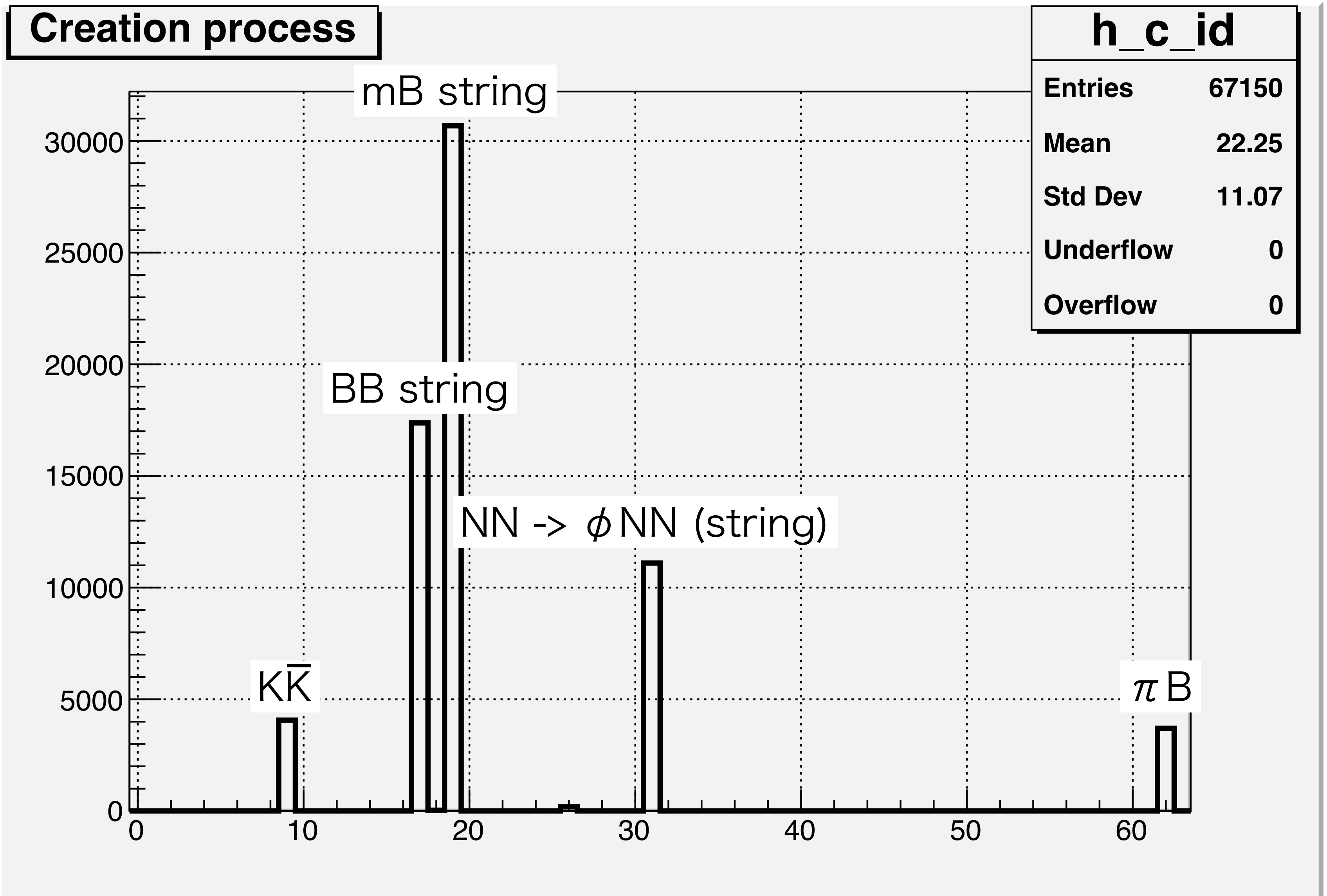
- If the density difference from the last mass change is >0.06 ρ_0, mass is re-calculated so that the cumulative probability matches the one of previous mass in the previous CDF. Energy is conserved and momentum is re-calculated.

Elementary output of PHSD

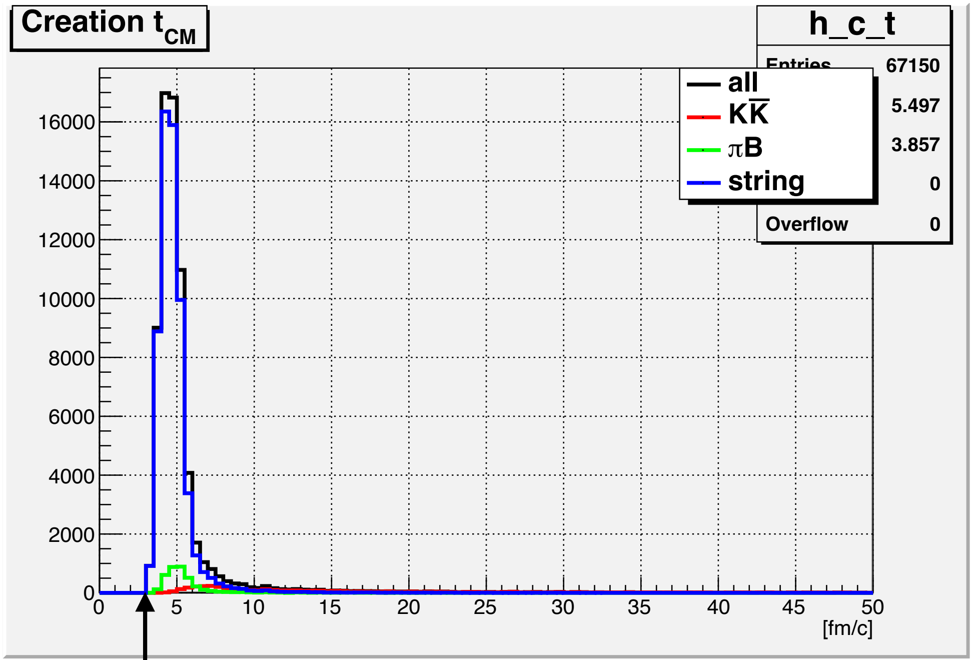
ϕ production: creation process

12 GeV p + Cu

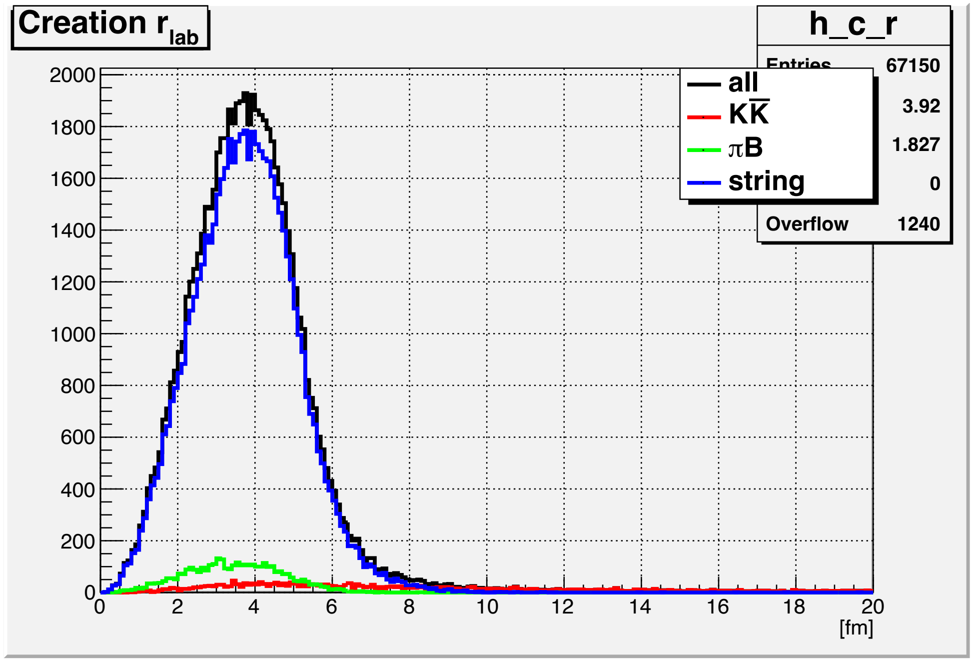
- string: ~90 %
- $K\bar{K}$: ~5 %
- πB: ~5 %



ϕ production

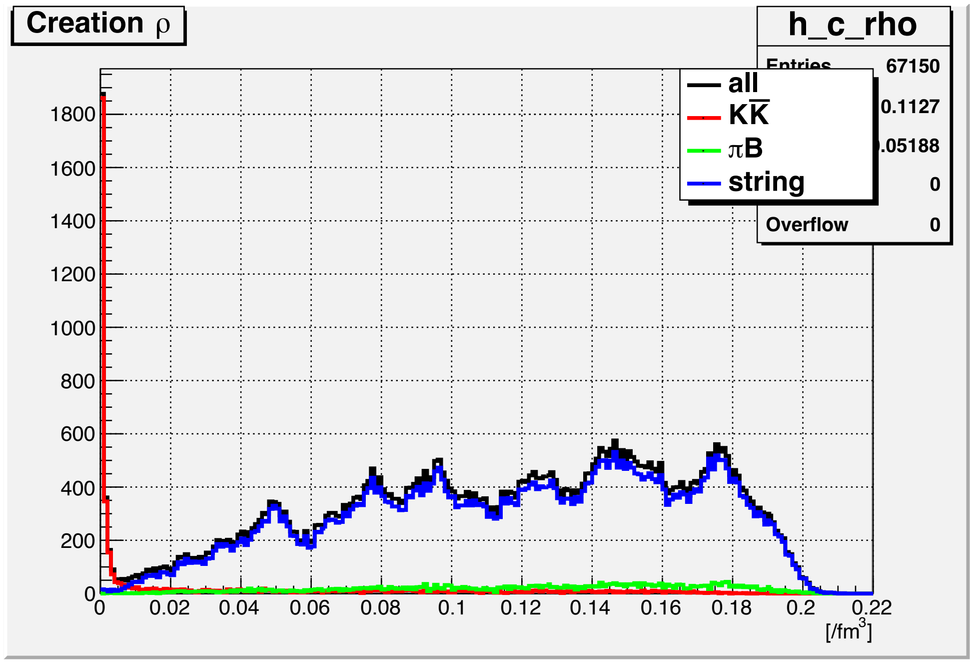


Collision timing

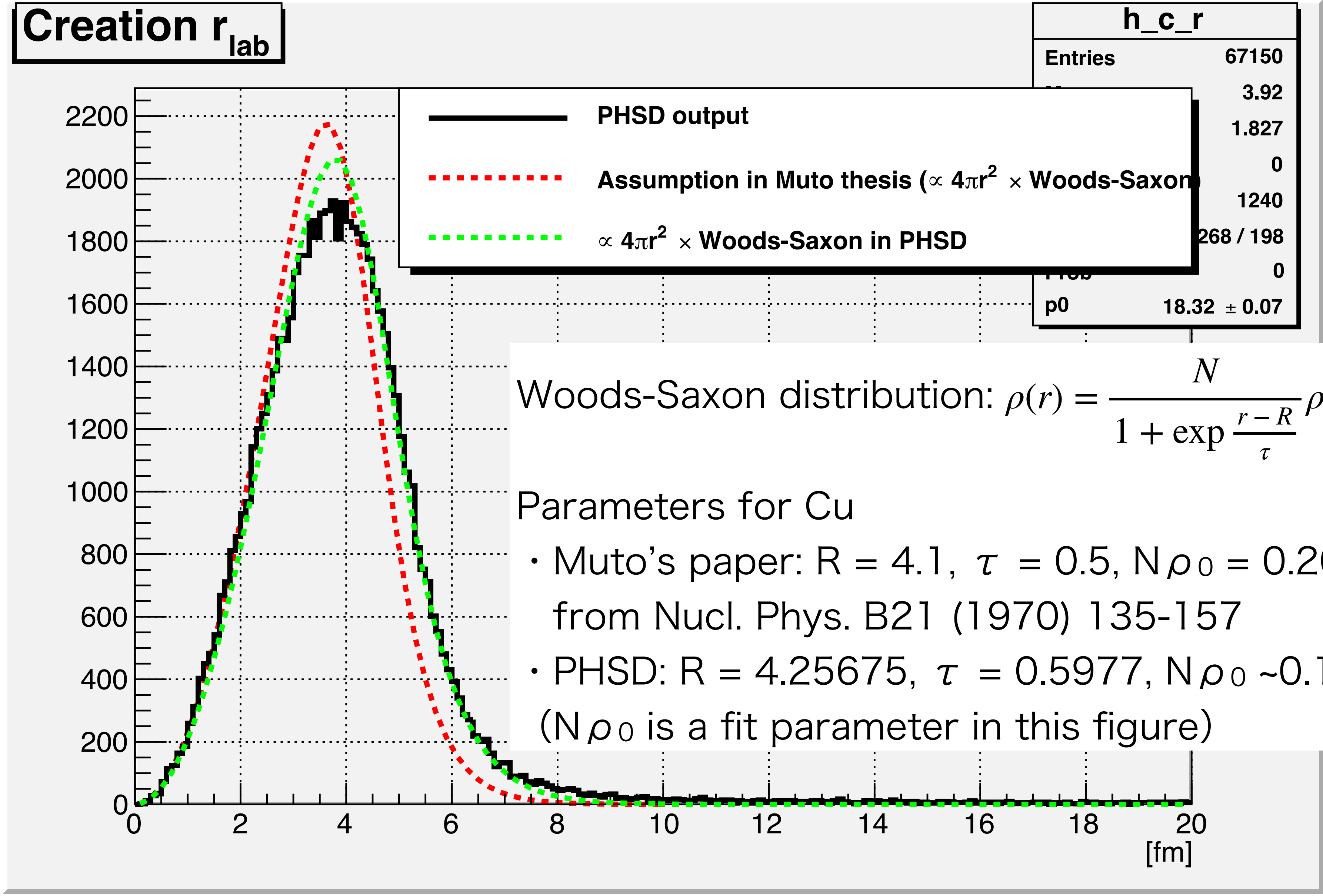


$K\bar{K}$ -> ϕ process occurs at

- Late timing
- Far from center of nucleus
- Low density



production point of ϕ



Woods-Saxon distribution: $\rho(r) = \dfrac{N}{1 + \exp \frac{r-R}{\tau}} \rho_0$

Parameters for Cu

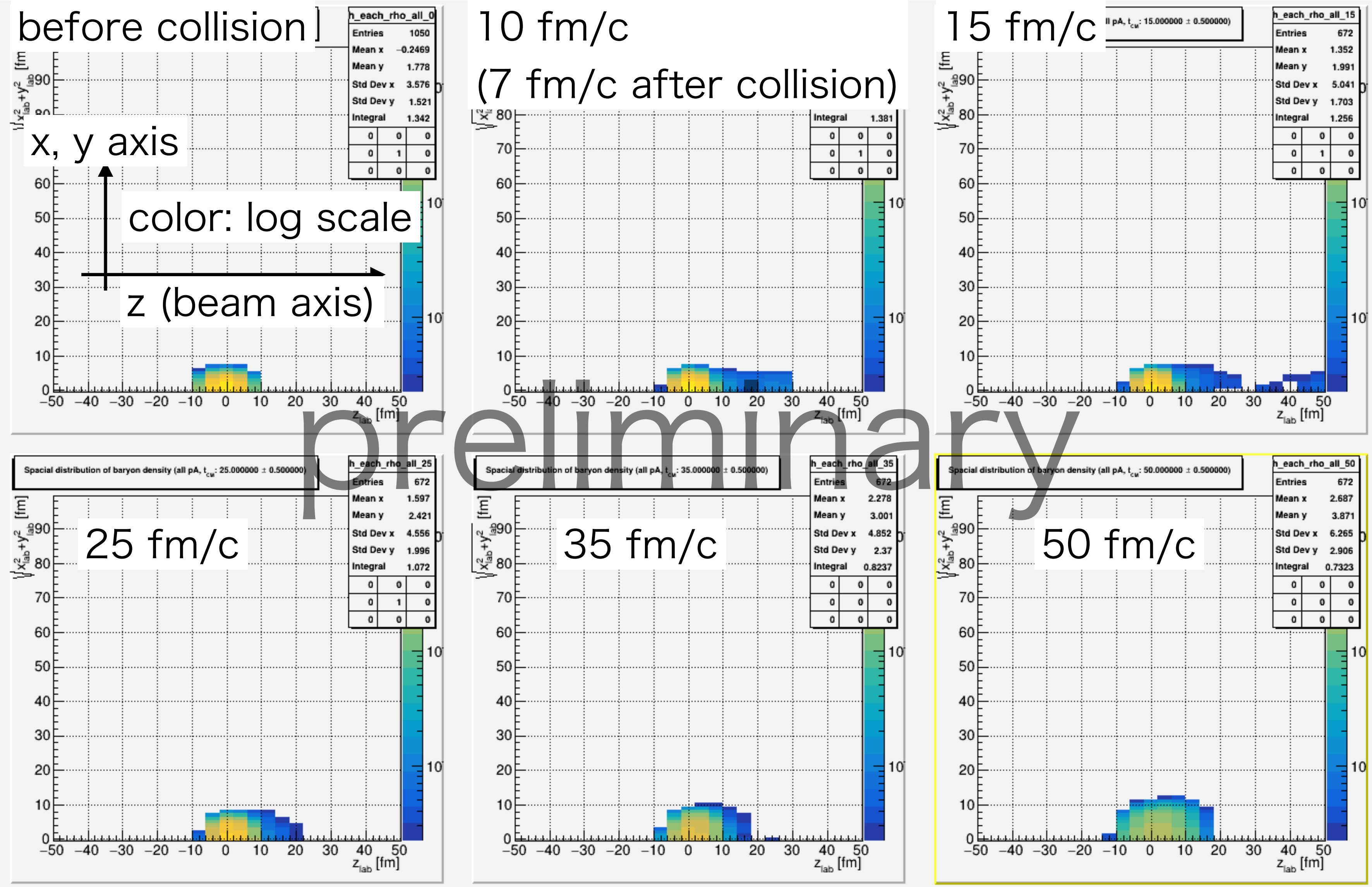
- Muto's paper: R = 4.1, τ = 0.5, $N\rho_0$ = 0.2016 from Nucl. Phys. B21 (1970) 135-157
- PHSD: R = 4.25675, τ = 0.5977, $N\rho_0$ ~0.166

($N\rho_0$ is a fit parameter in this figure)

- Production point distribution of ϕ largely follows Woods-Saxon distribution.
- The parameters of WS are different between Muto's analysis and PHSD.

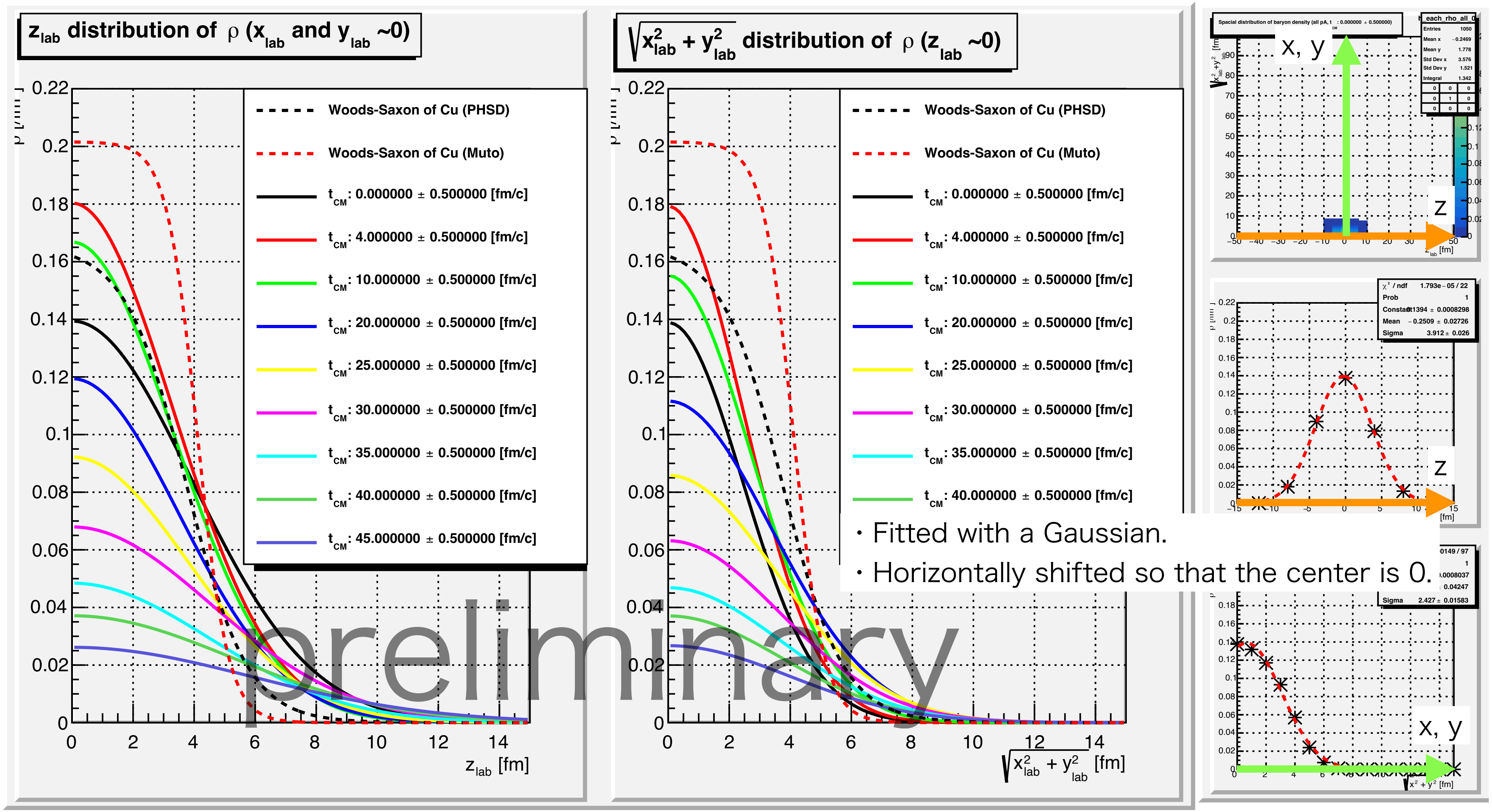
Time evolution of nucleons

Spacial distribution of baryon density (coordinate: lab system, density: CM system)



After the collision, some nucleons are stripped along the beam axis and then the nucleus is spread out in all directions?

Time evolution of nucleons



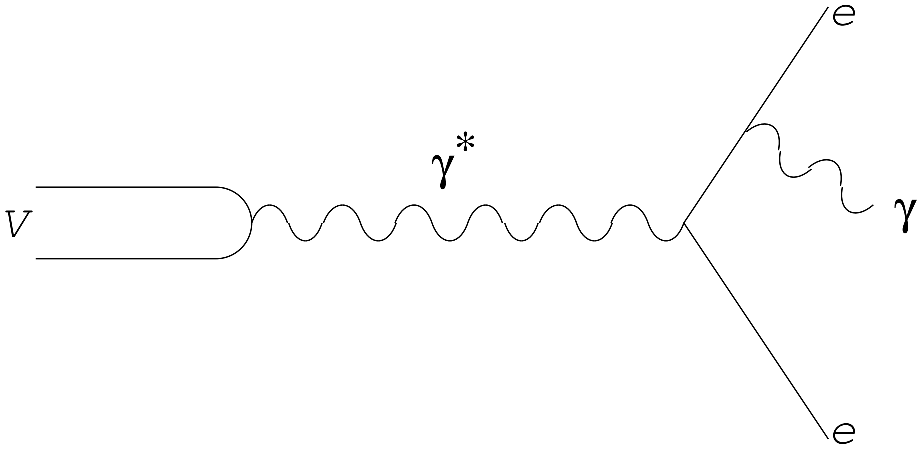
- Fitted with a Gaussian.
- Horizontally shifted so that the center is 0.

- The central density gradually decreases and the distribution broadens.
- The initial state differs significantly from the WS in the Muto's paper.
  <- Mainly due to the difference of WS parameters
- Time evolution of nucleus cannot be ignored.

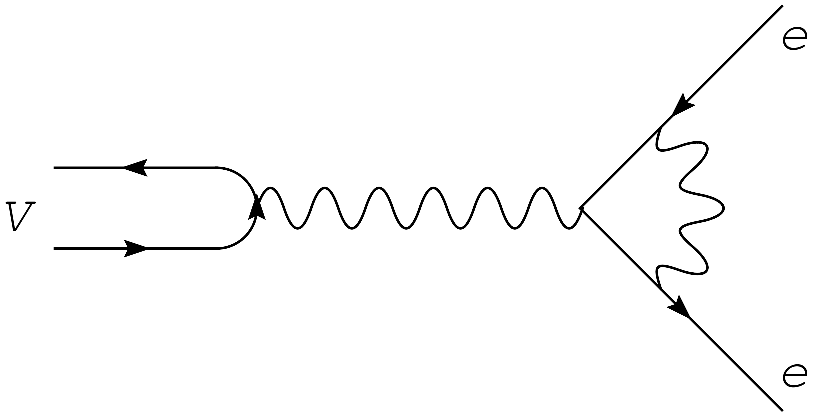
Application of PHSD to KEK-PS E325

Internal radiative correction (IRC)

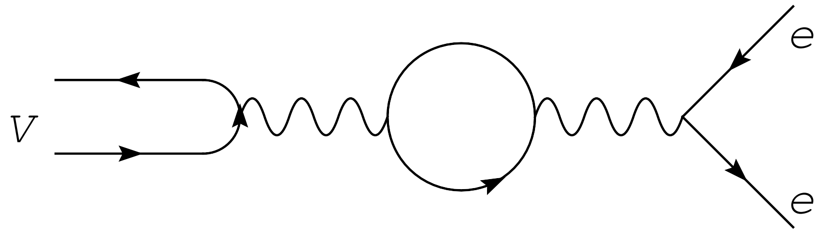
- The following physical processes distort invariant mass spectrum of e^+e^-.
- Using PHOTOS, we evaluate the effects on the ϕ decays in the PHSD output.
  - PHOTOS: Monte-Carlo for QED radiative correction



Internal bremsstrahlung

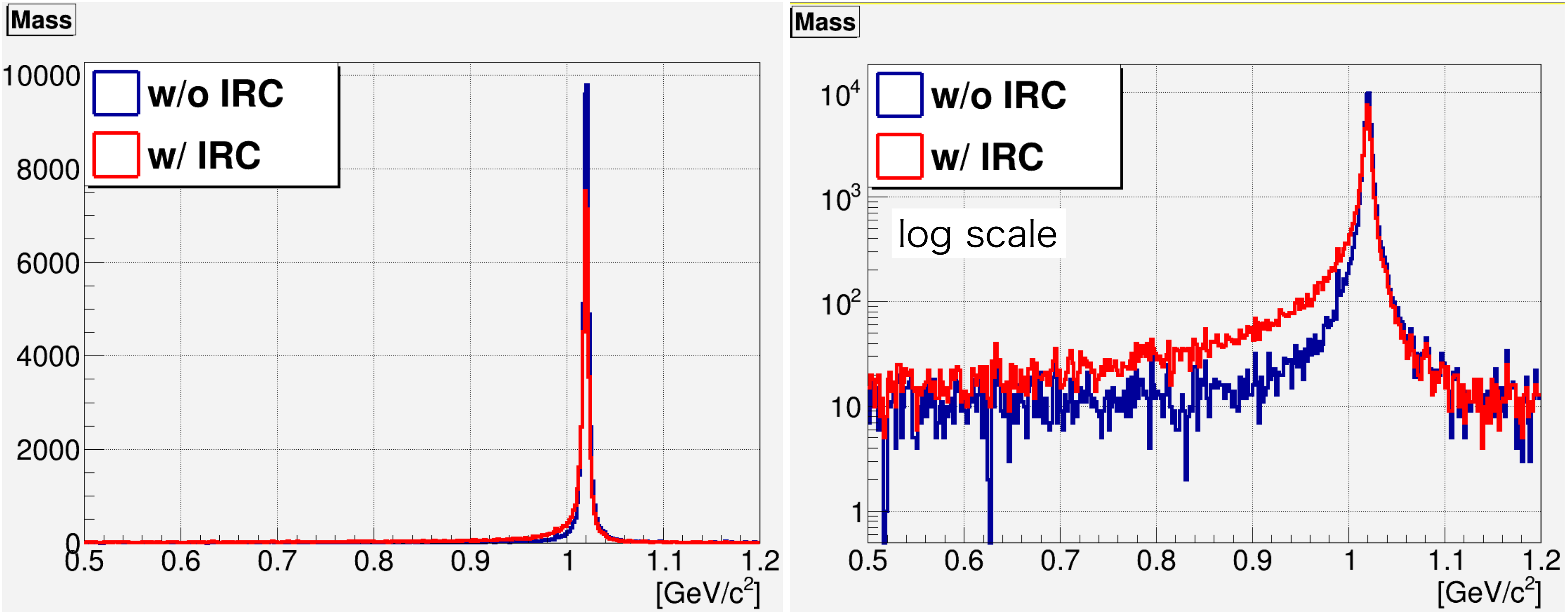


vertex correction



vacuum polarization

Internal radiative correction (IRC)



These effects resemble reduced mass scenario.

Experimental effects

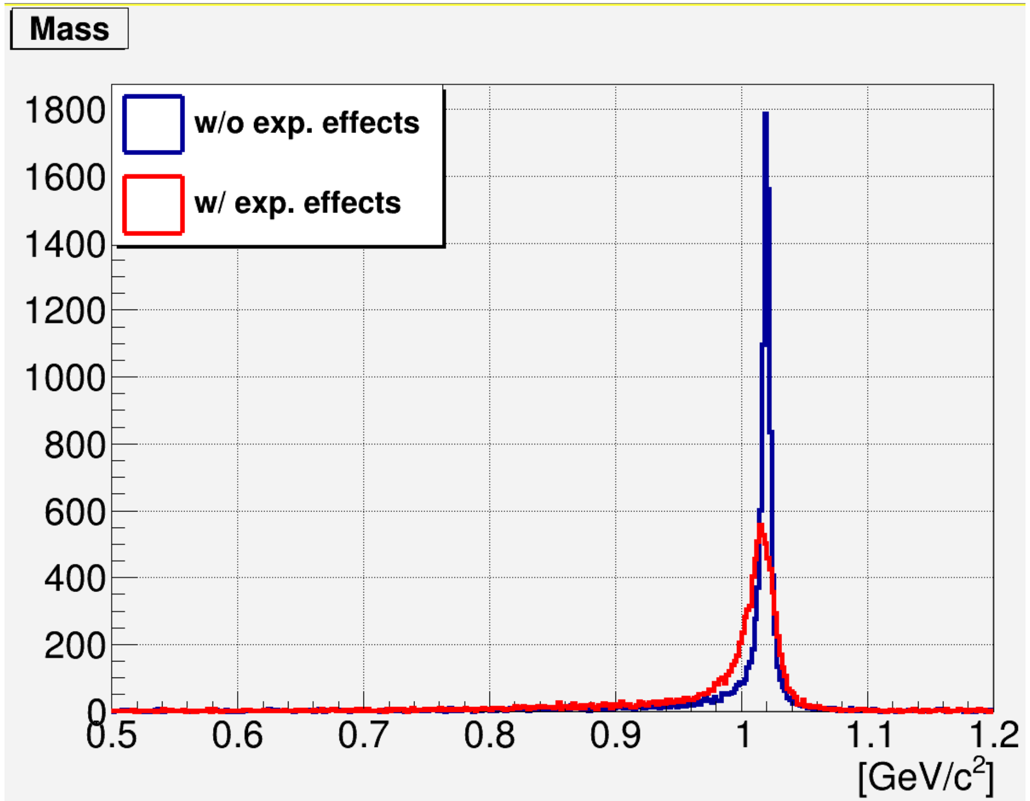
- Energy loss of e^+e^-
  - External radiative correction
  - Bethe-Bloch

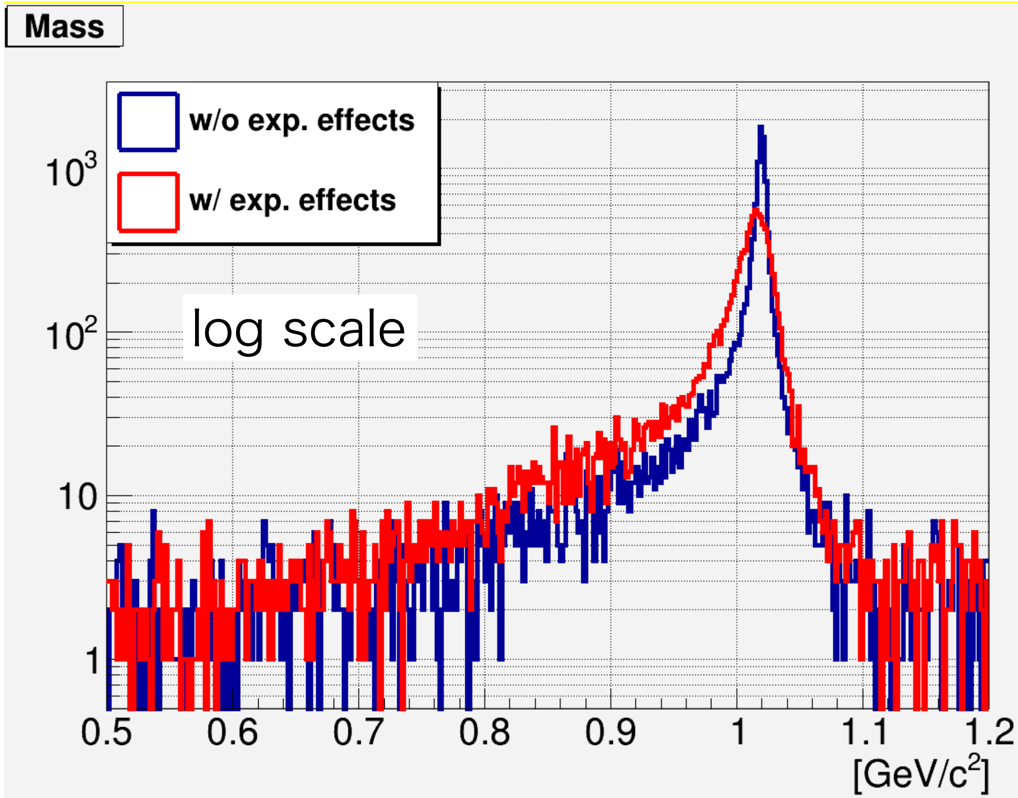
  -> Decrease measured ϕ mass.
- Position resolution of detectors

  -> Wider width of measured ϕ mass

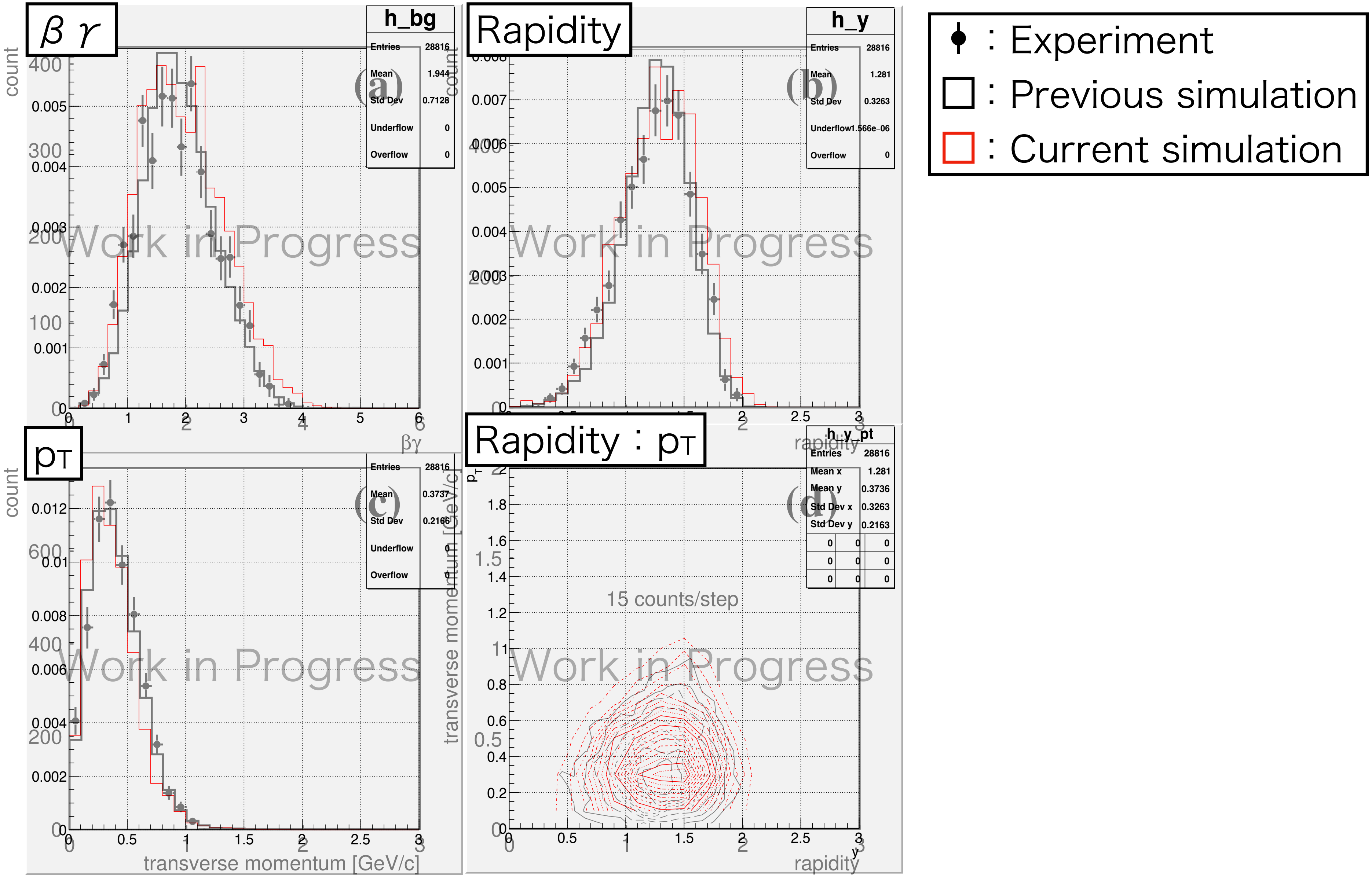
Using Geant4 to incorporate these effects.

Geant4: Monte-Carlo simulation of the passage of particles through matter





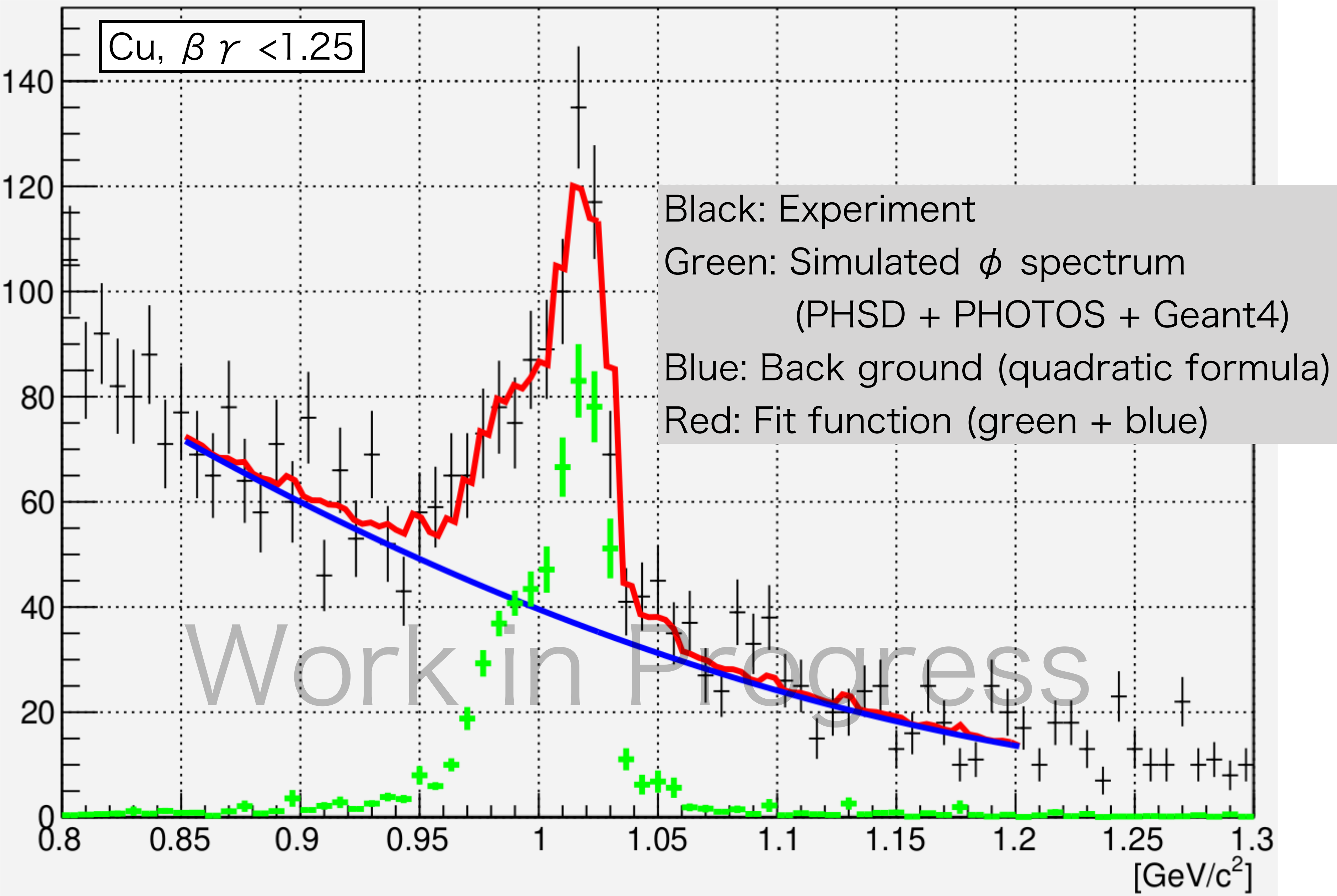
Momentum distribution



The momentum distribution of the current analysis (PHSD + PHOTOS + Geant4) almost reproduces that of the experiment.

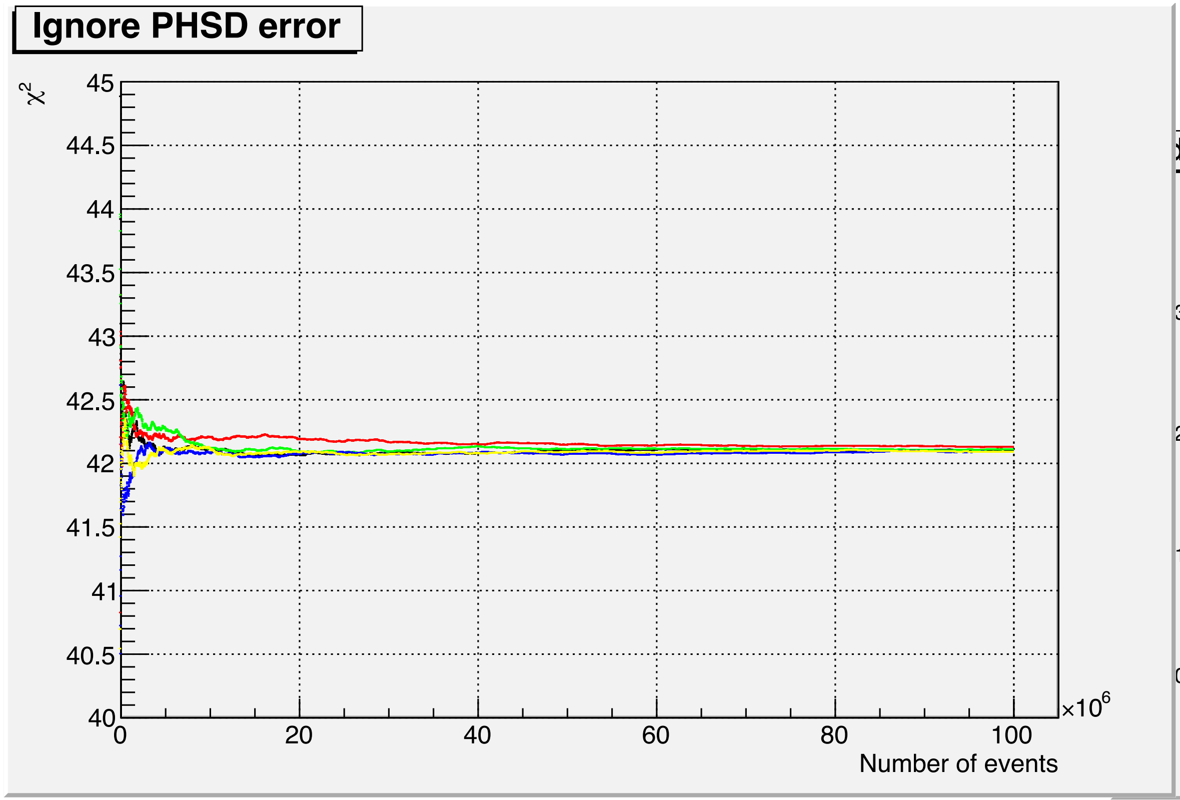
Current status

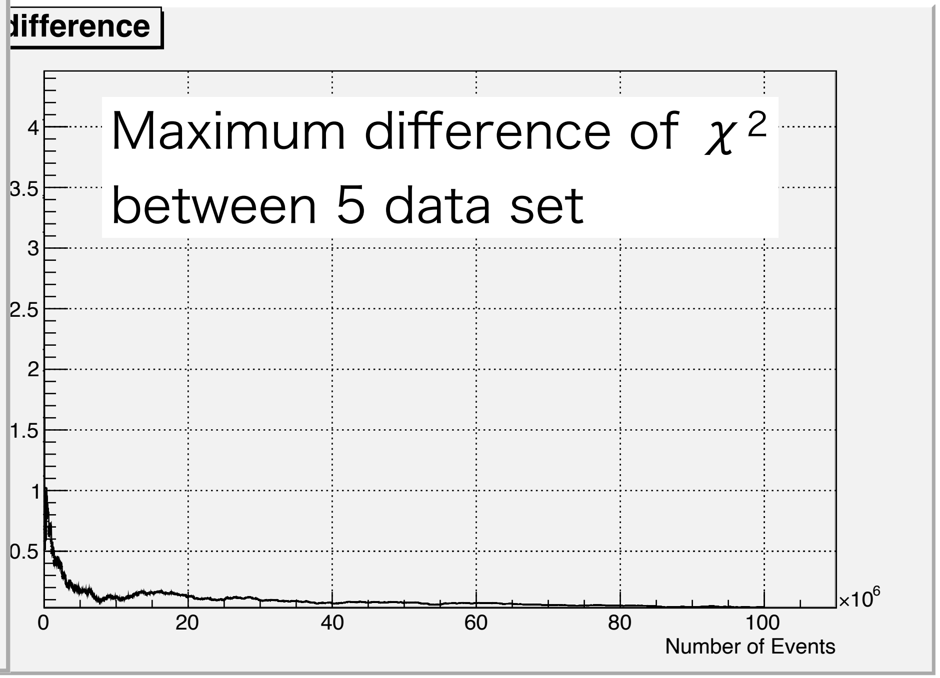
Methods for comparing PHSD with experiment is established.
All that remains is to increase the statistics of simulation.



Estimation of statistical requirement

- Based data (m, weight): PHSD + experimental effect
- Mass and weight are taken from the based data randomly and independently each other and make spectrum.
- Fit experimental data by the spectrum every 10,000 events and plot χ^2
- Repeat the above operation 5 times and compare each χ^2



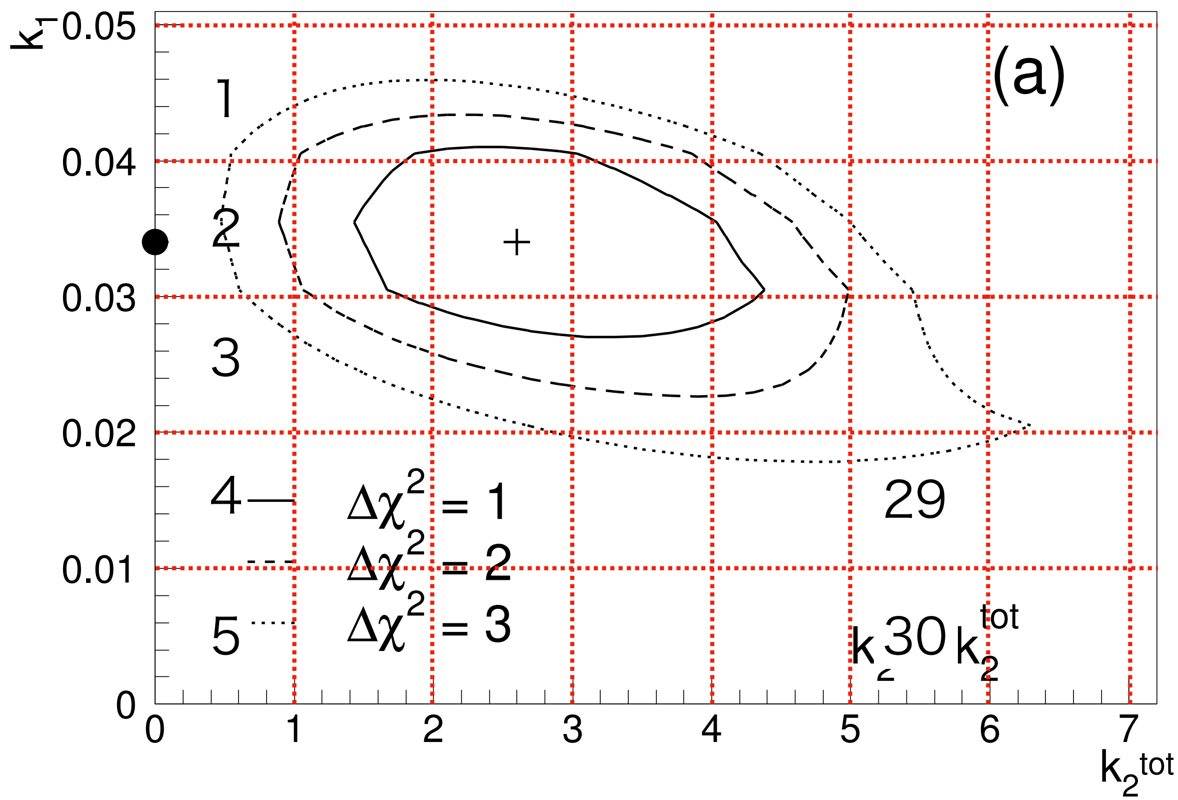


If we need χ^2 fluctuation < 0.1 for one target and $\beta\gamma$,
>10M events are needed (w/o correlation between steps).

Statistics of simulation

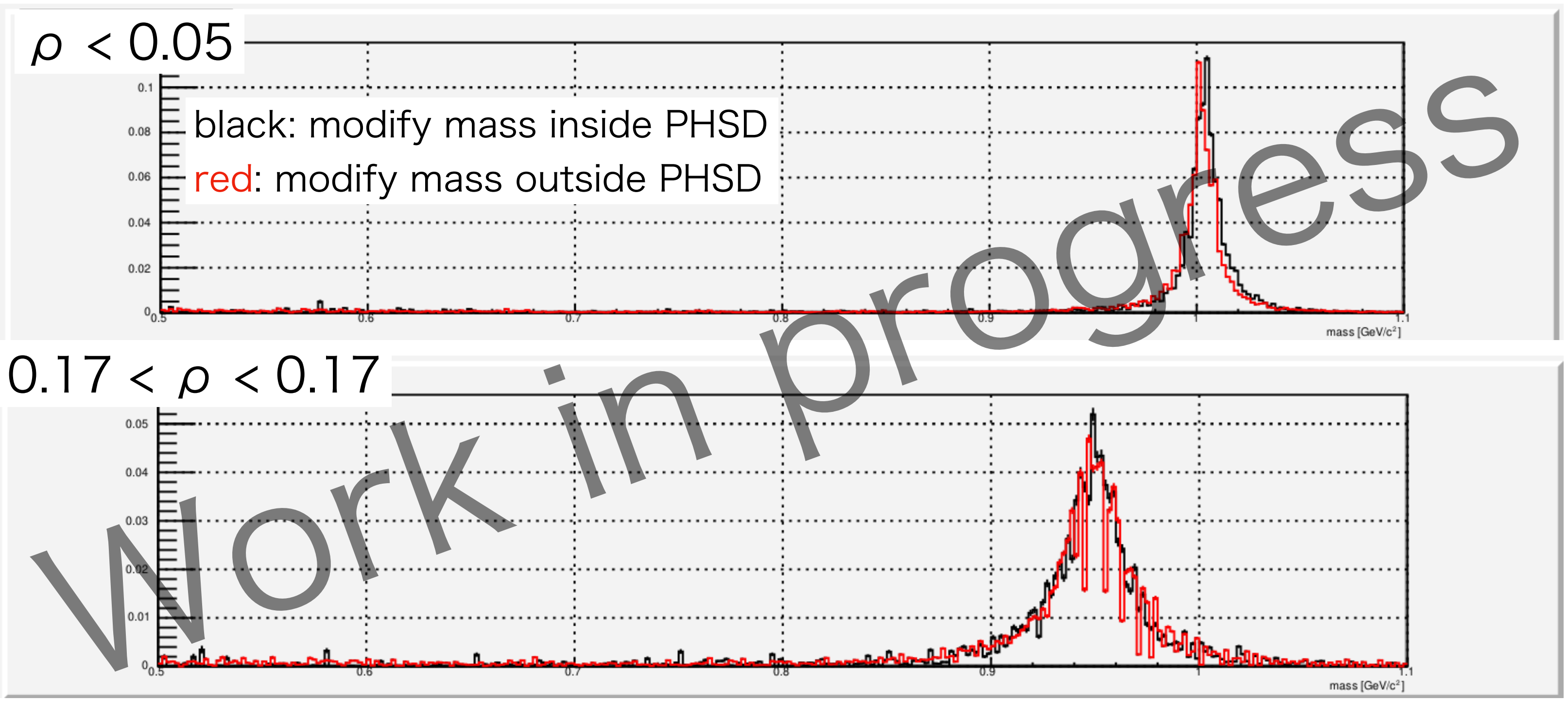
- Considering the detector acceptances of the E325 experiment for the momentum distribution obtained from PHSD, the statistics become ~10%.
- In PHSD, it is necessary to simulate pA reaction and ϕ production for each shift and broad parameter (unlike the previous analysis).

-> Need 1.5k cores and 9 months (for 30 parameters, current expectation)
CPU: Intel Xeon Max 9480 (1.9 GHz)



Attempt to reduce required statistics

- To reduce statistical requirements, we try adding shift and broadening parameter after PHSD.
- If it works, only two data sets (one for the base and one for the reference) are needed and the required statistics are reduced by 1/15.
- Using momentum and density distribution and modify mass by the method same as PHSD.



Statistics is insufficient, but systematic difference exists.

Summary

- Motivation
  - Measurement of spectral modification in an environment where chiral symmetry is partially restored.

- KEK-PS E325 experiment
  - p + A -> (ρ, ω, ϕ) + X, (ρ, ω, ϕ) -> e^+e^-
  - Significant spectral modifications in nuclear medium were observed.
  - By considering the density distribution after the pA reaction as Woods-Saxon,
    - Mass shift: -3.4%
    - Width broadening: 3.6 times

- PHSD
  - New approach to obtain more accurate information on
    - the production point of ϕ
    - the density distribution after pA reaction
  - These effects cannot be ignored.
  - Large statistics is needed to decide the best fitting parameters.

Methods for comparing PHSD with experiment is established.